Transonic Airfoil Shape Optimization in Preliminary Design Environment

Wu Li, Steven Krist, and Richard Campbell
NASA Langley Research Center

10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference
Albany, New York, August 30–September 1, 2004

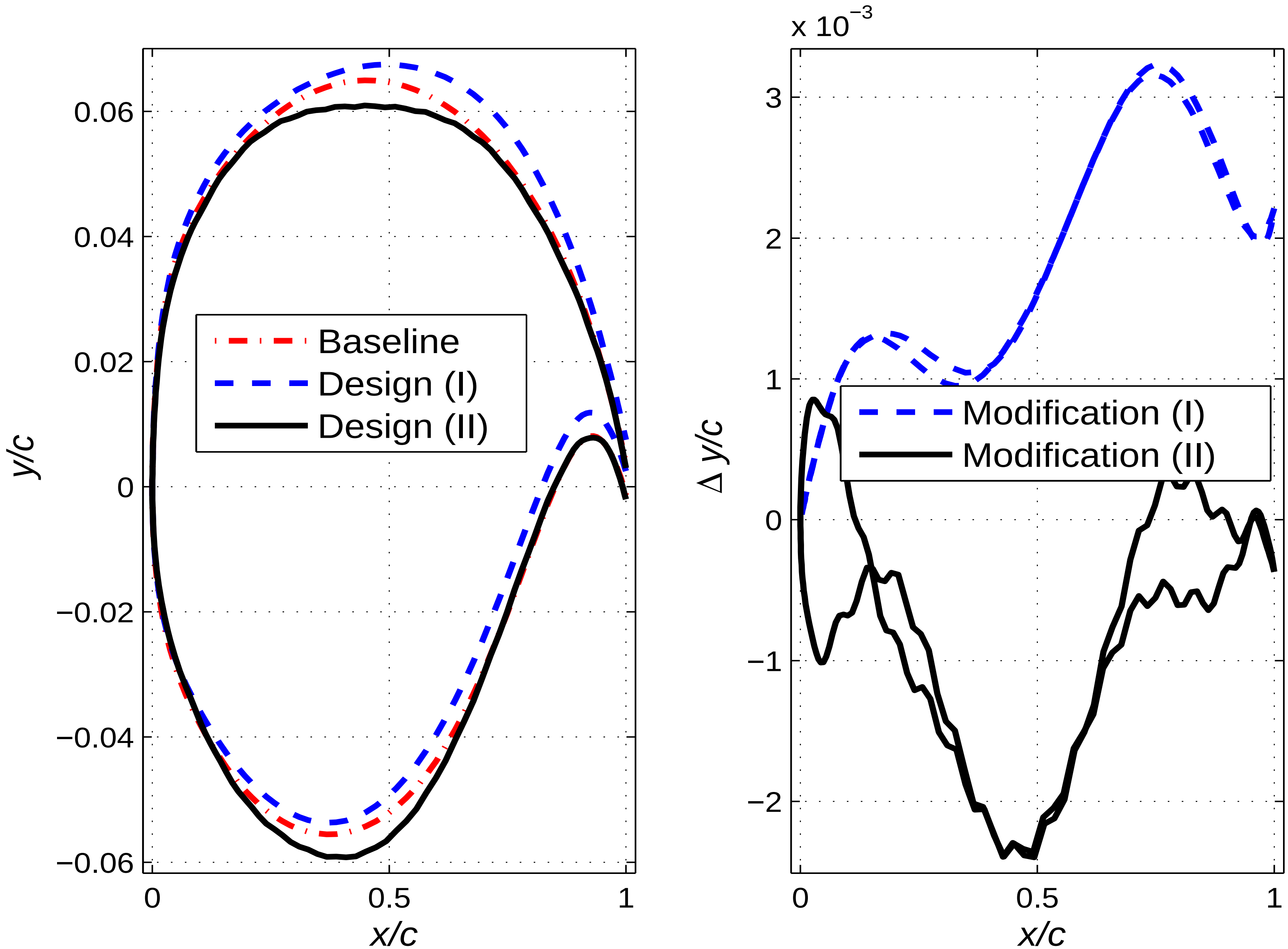
Outline

- Two new ideas for aerodynamic shape optimization:
  - Smoothest shape modification
  - Design-oriented multiobjective optimization
- POSSEM: Profile Optimization Method Using Smoothest Shape Modification
- Transonic airfoil design competition
- Comparison of three different airfoil designs generated by POSSEM and CDISC
- Lessons learned and concluding remarks

Difficulties of Aerodynamic Optimization in Preliminary Design Environment

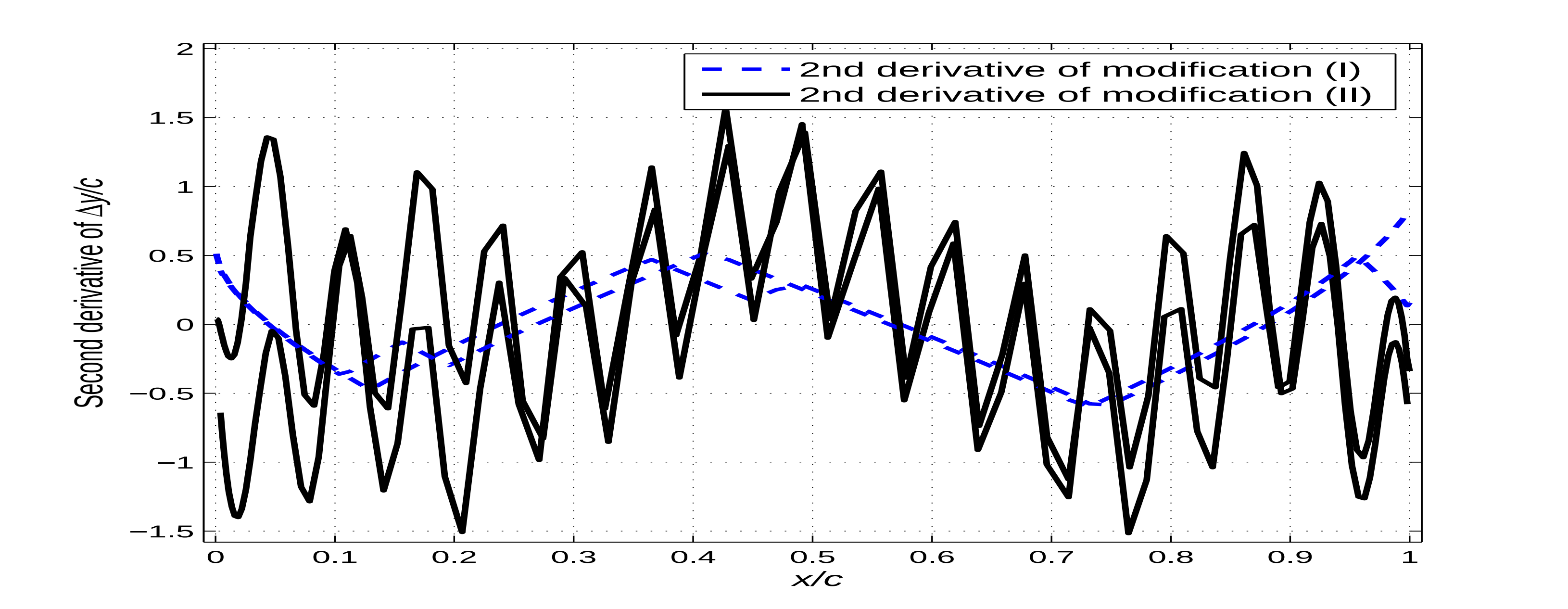
- It might be necessary to parameterize the design space by hundreds or thousands of design variables when searching for the last few percentage of performance improvement.
- Optimal solutions are not unique and depend on where the baseline is.
- Optimizer tends to exploit the lack of reality in a numerical optimization formulation and generates unrealistic designs.
- Optimizer tends to trade insignificant performance improvement at design conditions with severe off-design performance degradation.
- There is no standard optimization formulation that reflects vague and conflicting design goals.

Spline Representation of Airfoil Shape Modification



Formulation of Smoothest Shape Modification

- **Choice of Smoothness Measure**
  - Magnitude of $\Delta y''$ (the 2nd derivative of Δy)
- **Smoothest Shape Modification Scheme**
  - For a given predicted performance gain target, find $\Delta y(t)$ with the smallest magnitude of $\Delta y''$ that achieves the predicted performance gain.



Benefits of Smoothest Shape Modification for Aerodynamic Shape Optimization

- Improve the prediction accuracy of linear Taylor expansion of an aerodynamic coefficient.
- Reduce adverse effects of errors in the computed derivatives.

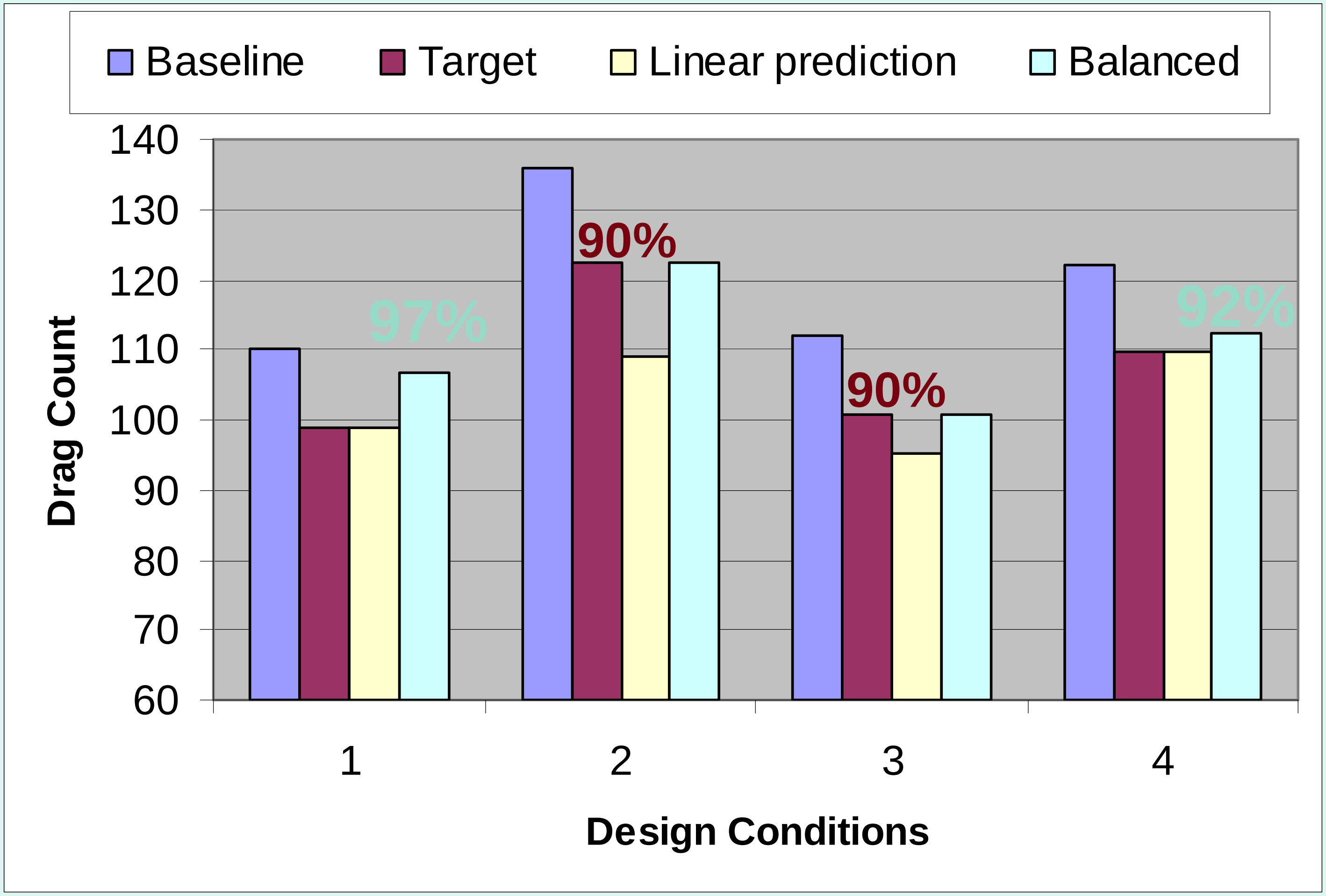
To obtain reliable predictions of the performance improvement by using a gradient-based optimization method, it is better to use small and smooth shape modification.

Design-Oriented Multiobjective Optimization

- Design Objective: Given performance metrics P_1, P_2, …, P_r, the objective is to modify the existing design so that the new design improves all the performance metrics (if possible).
- Dynamic Adjustment of Performance Gains: Find a new design that has a given predicted rate (say, 2%) of improvement over the existing design at one design condition and as much performance improvement as possible at the other design conditions.

The above optimization strategy is intended to mimic a designer's behavior during the design process, which can help the optimizer to focus on designs that a designer is likely to explore.

Dynamic Adjustment of Performance Gains



The performance gain factors dynamically balance the conflicting needs for performance gains at different design conditions.
The target drag reduction rate γ=10% is for illustration purpose.

Modified **P**rofile **O**ptimization Using **S**moothest **S**hap**e** **M**odification (**POSSEM**)

- Objective functions are the drag coefficients at r design conditions defined by r pairs of speed and lift coefficient, e.g., (M=0.76,CL=0.7) under nonlinear flow condition
- Constraints include thickness constraints and the specified target values for lift coefficients at r design conditions.
- Each iteration is determined by a target drag reduction rate γ and consists of another iterative process:
  1. Initialize the performance gain factors $\tau_1=\ldots=\tau_r=1$
  2. Find the smallest δ such that

     $|\Delta y''|\leq\delta$, the predicted drag coefficient for $y+\Delta y$ at the i^{th} design condition is at least reduced by a factor of $\tau_i\,\gamma$
  3. If the maximum reduction rate for the predicted drag coefficients is greater than γ at any condition, then reduce one of $\tau_1,\ldots,\tau_r$ by half and go back to step 2.

Design Competition for Validation of POSSEM

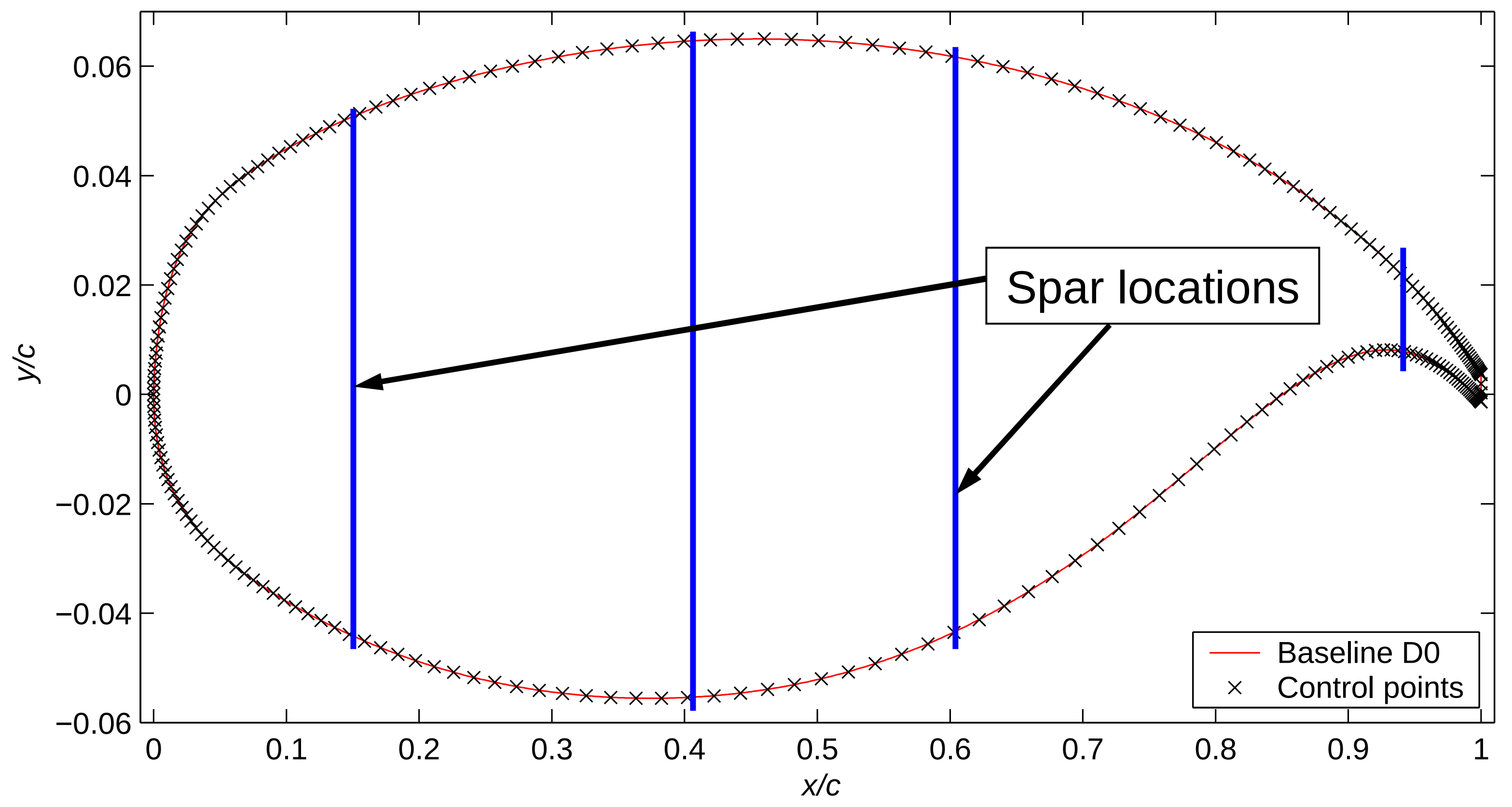
- Design Conditions: M=0.7, CL=0.7 (climb out performance); M=0.76, CL=0.76, 0.7, and 0.64 (start, mid, and end cruise conditions)
- Constraints: Maximum thickness must be 12% (of the chord length) and others
- Design Objective: Improve the baseline at the four design conditions as much as possible, while avoiding off-design performance degradation.
- Evaluation Metrics:
  - Small average drag at the four design conditions
  - Desirable drag rise curves for three CL values (0.76, 0.7, 0.64)

There are some qualitative statements in the formulation of the design competition, which is typical in a realistic design environment.

The Baseline D0 and Three Candidates

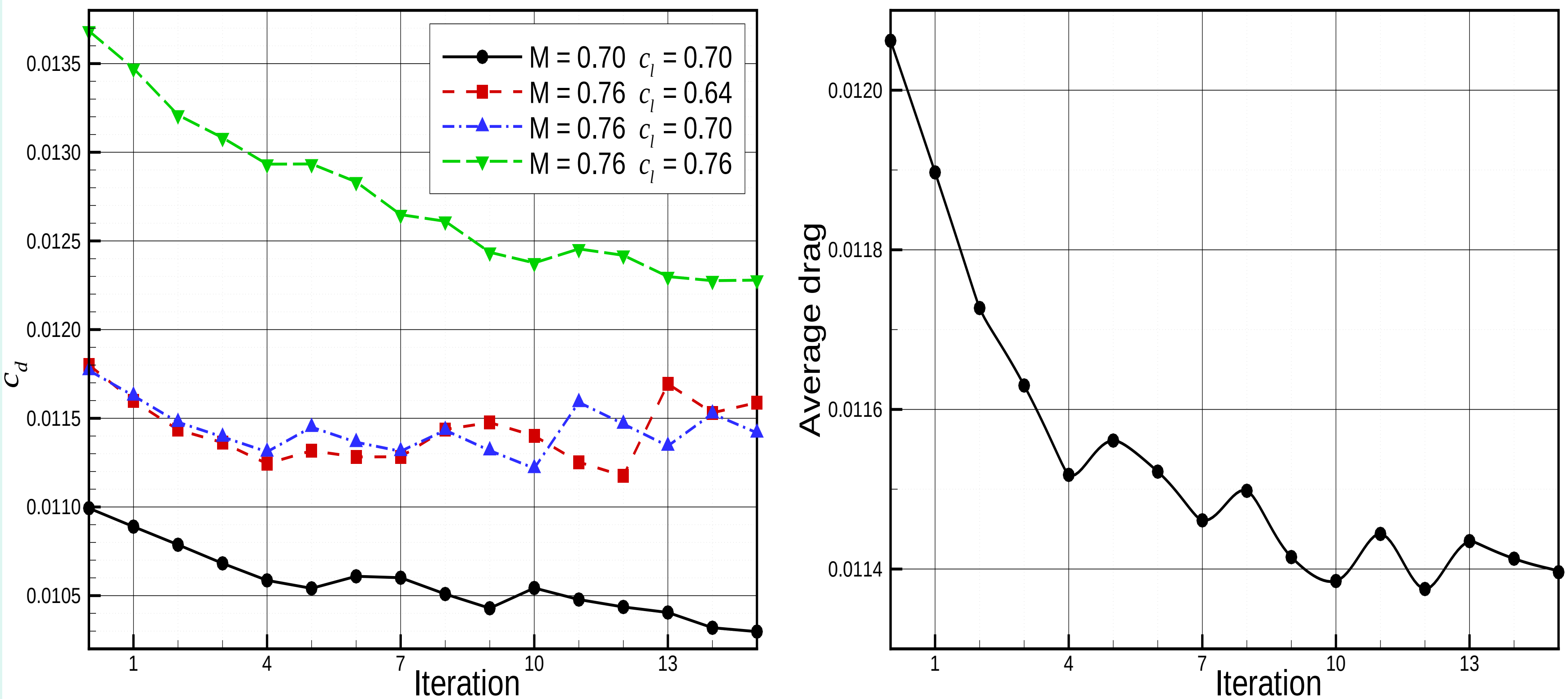
- The baseline is quite well-designed by using single point inverse design with CDISC/MSES.
  - CDISC/MSES design D0 reduces the average drag of a modified real-world airfoil by 18% at the four design conditions.
  - To demonstrate the capability of a new design method in a preliminary design environment, it is inappropriate to use a baseline that can easily be improved by 15% – 50%.
- D1 is generated by using two-point inverse design with CDISC and MSES (Euler flow analysis code).
- D2 is generated by using single point inverse design with CDISC and OVERFLOW (Navier-Stokes code), along with spline-based airfoil curvature smoothing.
- D3 is generated by POSSEM (with FUN2D Navier-Stokes flow and adjoint analyses).

Initial Set Up for POSSEM

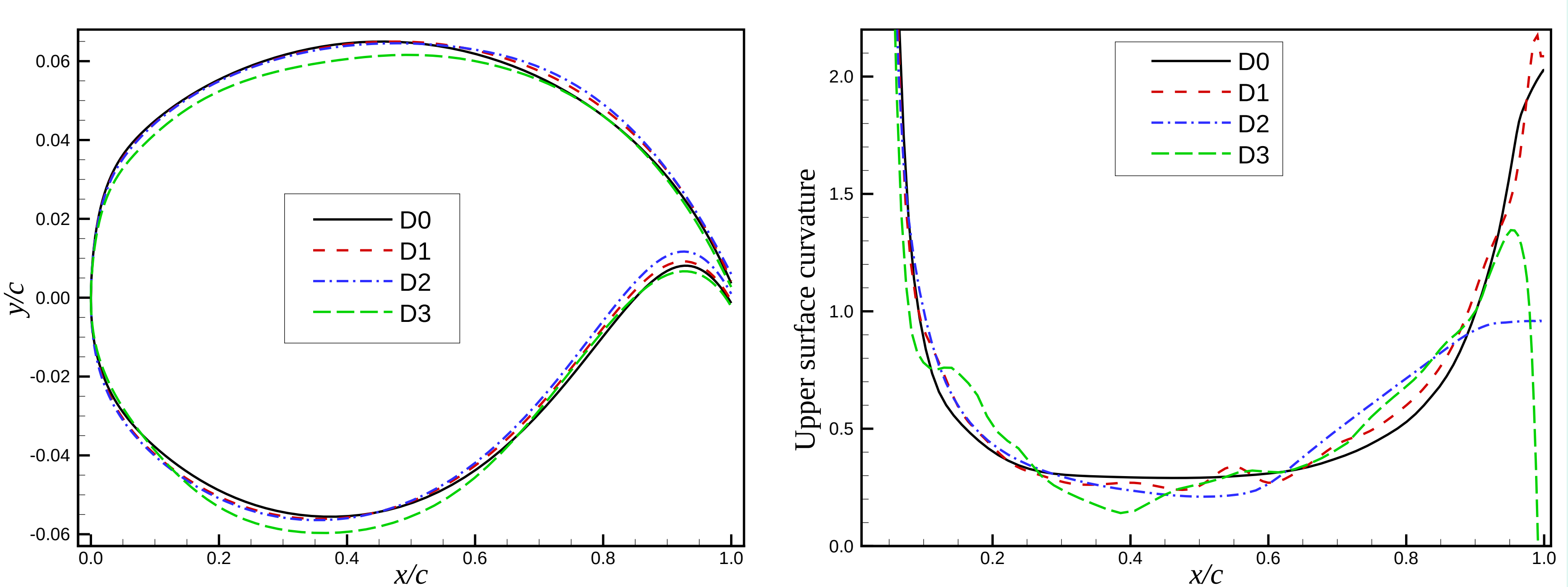


The 201 design variables are the y coordinates of the control points of the spline representation of the airfoil. Thickness constraints at four locations (indicated by blue lines) are used in POSSEM optimization.

Iteration History of POSSEM (D3=Iterate 10)



Airfoil Shapes and Curvature Profiles for All Designs



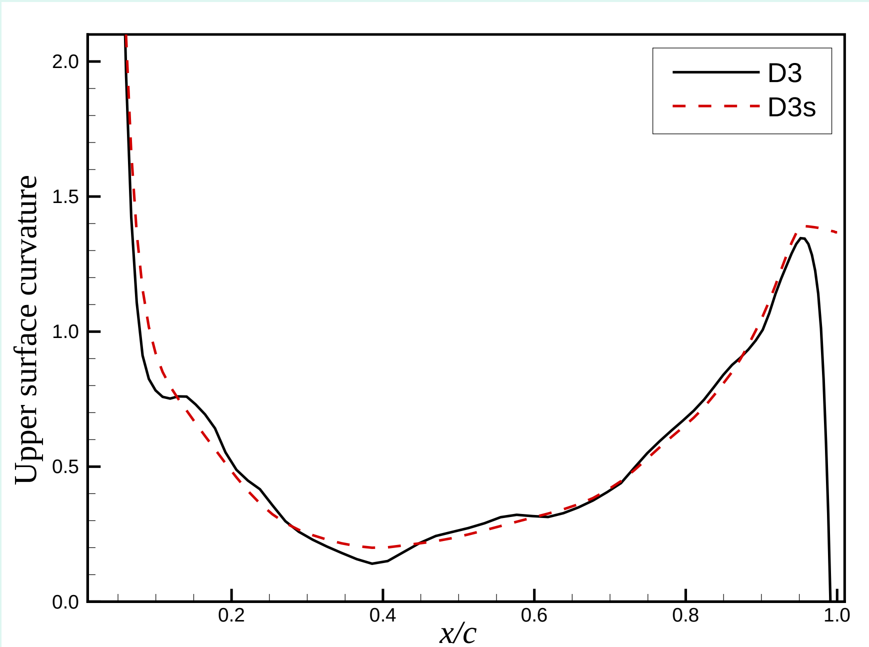
D0, D1, and D2 have smooth curvature because of post-processing by curvature smoothing, while D3 has minor curvature oscillations.

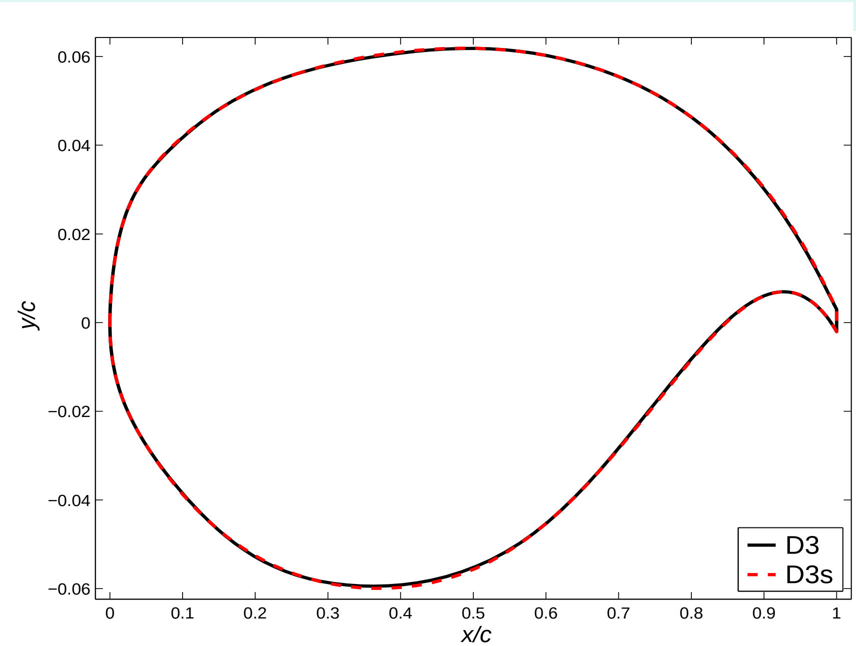
Summary of Average Performance at Design Conditions

	D0	D1	D2	D3	D3s
MSES	0.00960	0.00933	0.00938	0.00924	0.00924
OVERFLOW	0.01158	0.01141	0.01096	0.01096	0.01096
FUN2D	0.01171	0.01139	0.01095	0.01091	0.01086
Average	0.01096	0.01071	0.01043	0.01037	0.01035

Green shows the best performance and red shows the worst performance among D0, D1, D2 and D3. D3s is the smoothed version of D3 and has a better average performance than D3.

Difference Between D3 and D3s



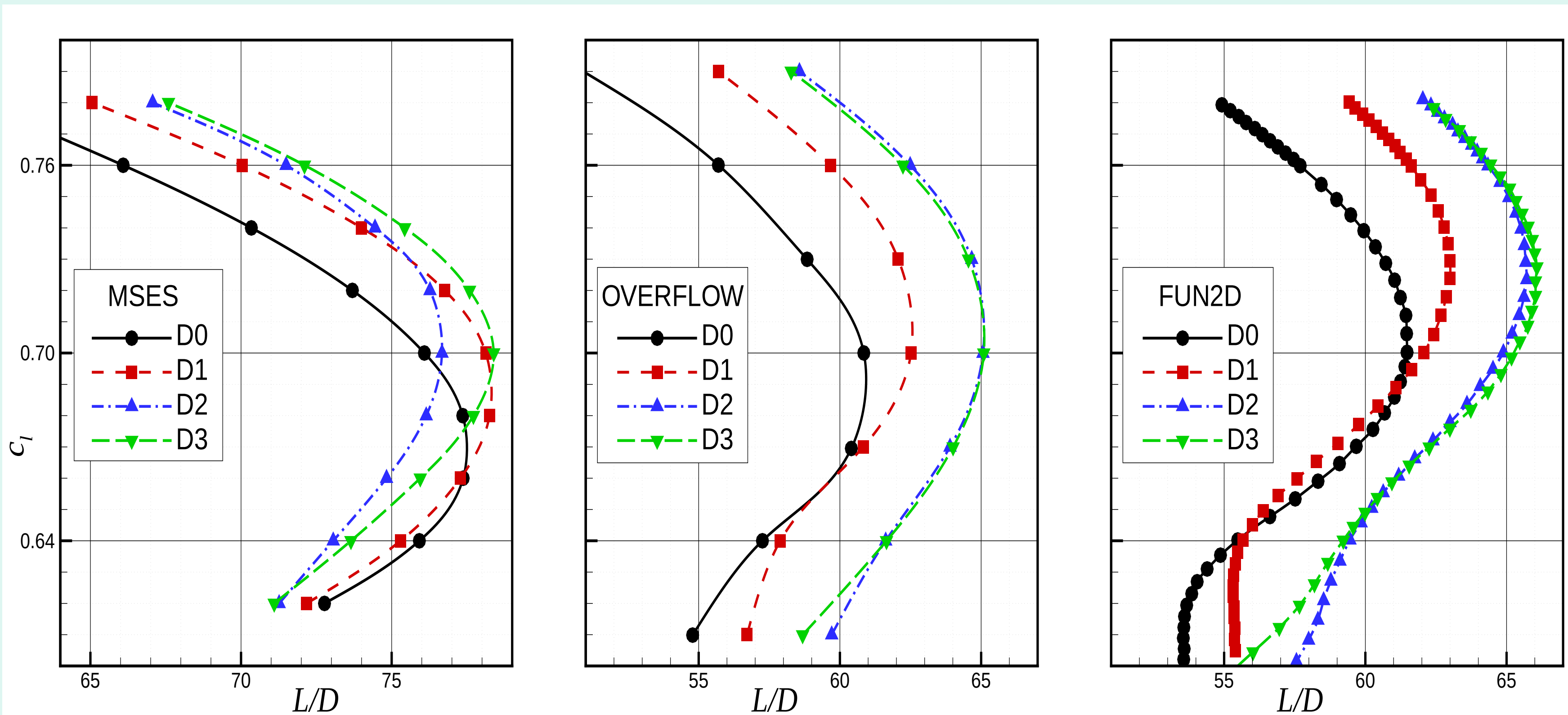


Difference in Geometry: Mean=0.00001, Max=0.0006

Difference in Curvature: Mean=0.05, Max=7.4

Open Question: Can one develop an optimization code that searches for the smoothest shape with a specified performance improvement?

L/D Plots at the Cruise Speed M=0.76



Lessons Learned

- The acceptance of a design/optimization method in practice depends on how realistic the test case is.
- Performance improvement of a design achieved by aerodynamic shape design/optimization method is likely code-dependent. Code-independent methods are highly desirable.
- A practical aerodynamic shape optimization code should avoid exploiting the lack of reality in the problem formulation or numerical uncertainty in simulation analysis results.
- Choice of the best design is a multi-criteria decision making process.

Concluding Remarks

- POSSEM is an optimization algorithm that uses two key ideas: smoothest shape modification and design-oriented multiobjective optimization.
- The optimal airfoil generated by POSSEM is “better” than the airfoils designed by experienced designers and as realistic as those generated by designers.
- Smoothest shape modification and design-oriented multiobjective optimization are applicable to 3D aerodynamic shape optimization in theory.

The (x,y) coordinates for the five airfoils studied in this paper are available for download at

http://mdob.larc.nasa.gov/staff/wli